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INTERSTELLAR Ca II LINES IN SMC STARS[a]

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ABSTRACT

Interstellar Ca II lines of reddened early-type stars in the SMC were observed. In addition to the component from the Milky Way, strong lines were detected at radial velocities corresponding to gas in the SMC. The interstellar Ca II lines are abnormally strong, given the small color excesses of the stars and the low metallicity of the SMC gas, which suggests that the grains contain a much smaller fraction of the interstellar calcium than they do in our galaxy. The radial velocities do not conflict with the two-galaxy model for the SMC of Matthewson and Ford (1983) if the higher-velocity system is behind the lower-velocity system.

I. INTRODUCTION

The interstellar medium in nearby galaxies can now be explored through detailed 21-cm maps of H I, CO observations at mm wavelengths with moderate spatial resolution, and UV absorption lines from satellites. However, there have been few studies of optical interstellar lines arising in the gas of other galaxies, and most of these have concentrated on the possibility that extended spiral disks can produce quasar absorption-line systems (see, for example, Boksenberg and Sargent 1978). Because the Small Magellanic Cloud is metal poor, gas rich, and has a high current rate of star formation, its interstellar medium may be quite different from that in our own galaxy. The SMC is close enough that *IUE* observations of individual stars are feasible. Rocca-Volmerange *et al.* (1981) (see also the review by Nandy 1983) have shown from comparing the continua of reddened and unreddened eary-type stars that the slope of the extinction curve in the far UV is much steeper than in the Milky Way. The analysis of *IUE* data on UV absorption lines in LMC and SMC stars has been reviewed by de Boer (1983), but in general the only lines that can be detected at present in spectra of MC stars arise from high stages of ionization such as C IV; these lines are presumably formed in an extended hot halo or corona, rather than in the general interstellar medium of a galactic disk.

Previous studies of the optical interstellar lines in the SMC are extremely limited. Feast, Thackery, and Wesselink (1960) and Ardeberg and Maurice (1977) reported a few detections of interstellar Ca II from low-resolution spectra, while Songaila and York (1980) (see also Songaila 1981) observed three SMC stars at high spectral resolution. We present here a study of the optical interstellar Ca II line at 3933 Å in a group of highly reddened early-type stars in the SMC. The spectra are described in Sec. II. The results are discussed in Sec. III, where a comparison with recent high-sensitivity 21-cm H I maps is given. The final section contains a summary.

II. OBSERVATIONS

A sample of reddened early-type stars which are members of the SMC was selected from the tabulation of Azzopardi and Vigneau (1975). We observed 31 SMC stars in September 1982 with the intensified reticon detector constructed by Shectman (1978) at the 2.5-m duPont telescope of the Las Campanas Observatory in Chile. The fully sky-subtracted spectra were taken through pairs of apertures 1 × 4 arcsec in size. The 1200 grooves/mm grating was used to give 0.29 Å/pixel or 0.72 Å resolution. Comparison arc spectra were taken before and after each star. The spectra contain from 400 to 1000 detected photons per pixel in the continuum at 3930 Å, corresponding to signal-to-noise ratios of 20–30.

The spectra were divided by that of a flat-field lamp to remove the pixel-to-pixel variations. Sections from 3870 to 3980 Å of a sample of flattened spectra are shown in Fig. 1; the vertical axis is approximately raw counts. The stellar radial velocities were determined by cross correlating the region from 3830 to 4190 Å using three of the best SMC spectra as templates, while the radial velocities of the interstellar features were measured by hand from enlargements of each spectrum in the region of 3930 Å. The zero point of the stellar radial velocities was set using the 17 stars in the sample with previously published (but lower accuracy) radial velocities from Ardeberg and Maurice (1977).

Since the spectra are well exposed with lines whose full width at half maximum is 55 km/s, the stellar radial velocities should be quite accurate ($\pm$ 10 km/s). The radial velocity of the galactic interstellar component is given when it could be measured, but the errors are substantially larger. The quoted accuracies of our radial velocities are supported by comparing the Ca II 3933 Å and stellar radial velocities measured for the seven SMC stars with spectral types later than B5 (whose Ca II lines are probably stellar rather than interstellar). The mean of the difference is $-$ 2.7 km/s with a dispersion about the mean of 9 km/s. For the objects in common, a dispersion about the mean of 16 km/s is obtained for the differences between our stellar radial velocities and those of Ardeberg and Maurice (1977) (who used photographic spectra with a dispersion of 74 Å/mm).

Rough equivalent widths of the SMC interstellar components were also measured, excluding when possible the galactic contribution to the line. The data are listed in Table I. In the first column is the number of the star in the list of Azzopardi and Vigneau (1975), while the second column gives the identification in the list of SMC members by Sanduleak (1968). The third column gives the spectral types taken from the work of Ardeberg and Maurice (1977), or if the value is given in parentheses, from Azzopardi and Vigneau. The $B-V$ color index is in the fourth column, from Azzopardi and Vigneau, Isserstadt (1978), or Ardeberg (1980). If the star has more than one photometric observation, the

[a] Based on observations obtained at the Las Campanas Observatory of the Carnegie Institution of Washington.

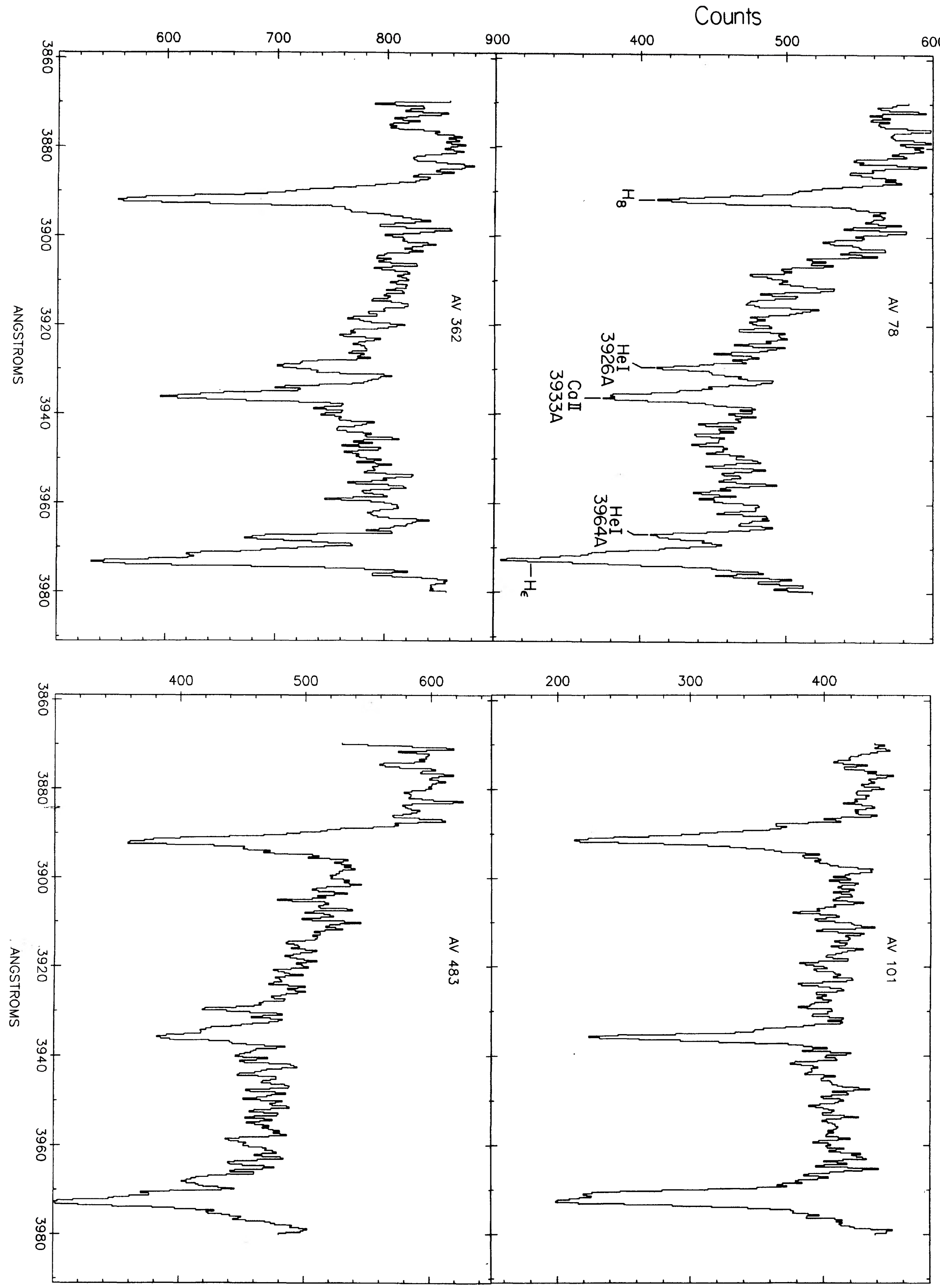

FIG. 1. Sample of spectra of SMC stars in the region from 3870 to 3980 Å. The vertical axis is approximately raw counts.

TABLE I. SMC interstellar Ca II lines.

AV #	San #	Sp. Type	$B-V$	W_λ 3933 Å	V_r 3933 Å	V_r Stellar	V_r H I (km s^{-1})
2	3	B6IaO:e	0.04	790	142	126*	134 164
4	5	(B0)	0.10	(180)	(207), (21)	P Cyg	137 162
6	—	(B0)	0.03	(280)	132,32	79	133 163
16	11	(B1)	0.12	460	145,7	P Cyg	133 163
23	17	(B0)	0.07	710	139, − 16	161	138 168
26	18	07 + neb	− 0.18	450	132,32	152*	136 168
34	—	(B2)	0.20	(520)	157	181	135 170
39	25	(B0)	0.01	470	145,7	162	135 170
48	27	B3Ia	− 0.02	480	124, − 18	148*	139 169
56	31	B2Ia	0.00	370	140,16	149*	133 168
65	33	B6Ia	0.12	720	157	163*	136 168
71	36	(B0)	− 0.01	< 220	—	159	126 161
78	40	B3Ia:	− 0.03	255	199,132	170*	139 169
98	45	B9Ia	0.05	540	182	189*	132 172
101	47	(09)	0.07	850	149,15	165	134 174
125	52	(09)	0.05	580	160, − 27	177	137 174
132	—	(B2)	0.09	290	140,215	164	137 174
214	—	(B0)	0.07	370	150, − 17	159	128 168
229	78	Wp + 0B + neb.	− 0.20	490	149	169*	128 168
232	80	08f + neb.	− 0.20	230	133,17	167*	128 168
242	85	B1.5Ia	− 0.11	480	141, − 8	148*	128 168
287	101	(09)	0.00	370	150,25	72	141 181
362	114	B3:Ia	− 0.02	370	191,25	215*	132 197
367	117	B7:Ia	0.07	405	215,41	213*	132 197
390	123	(B1)	0.03	230	166,33	P Cyg	138 198
415	130	B9IaOe	0.10	700	182,32	186*	133 178
443	137	B3IaO:	− 0.06	< 200	—	236*	135 180
456	143	(B0)	+ 0.10	420	150,75	164	139 179
475	152	A0 − A1IaO	0.13	585	190,32	201*	143 173
483	156	B1.5Ia	− 0.11	275	158,25	195*	138 168
504	168	B9Ia	− 0.03	375	183, 33	172*	138 188

mean of the $B-V$ colors is given. The next column lists the rough equivalent width of the SMC interstellar line of Ca II at 3933 Å, while the sixth column contains the measured heliocentric radial velocities of the components of the Ca II feature. The stellar heliocentric radial velocity is given in the seventh column. An asterisk following the velocity indicates that the object has a previously published velocity and was used to determine the zero point of our radial velocities. For the three stars with P Cygni profiles of the Balmer lines, the stellar radial velocity was not measured. The last column lists the peak H I velocities from Matthewson and Ford (1983).

III. DISCUSSION

a) The Strength of the Interstellar Ca II lines

The large sample of SMC stars presented here confirms the earlier suspicion of Songaila and York (1980) that the SMC interstellar Ca II lines are surprisingly strong. These stars are metal poor with spectral types of B3 or earlier, so the stellar contribution to the Ca II line must be small. The foreground color excess for the SMC is only 0.02–0.04 mag (Feast, Thackeray, and Wesselink 1960; McNamara and Feltz 1980). The SMC component of 3933 Å is often five times stronger than the galactic component, which is usually marginally detectable. The SMC supergiants have interstellar Ca II lines which are typical of galactic supergiants with color excesses between 0.4 and 0.6 mag (see, for example, Cohen 1975), but the SMC stars studied here have color excesses of about 0.2 mag. Galactic rotation along the line of sight to a distant Milky Way supergiant produces a variation of the radial velocity of the gas at each point, which in turn makes the interstellar lines of distant objects stronger, depending on galactic longitude (Spitzer 1948). This effect is presumably absent in the SMC stars. However, the effect is much too small (see Cohen 1973) to compensate for the fact that the interstellar medium of the SMC is metal poor by a factor of 5 to 10 (Dufour 1983).

Thus, as in the galactic halo (see Cohen and Meloy 1975), the interstellar Ca II lines in these SMC stars are abnormally strong for their reddenings. This could be the result of either of two factors: a difference in the ionization of the interstellar medium (henceforth abbreviated IM) or an absence of grains. In the IM in our galaxy, much of the calcium is in the form of Ca III, with the ratio of Ca/Ca II being a few (Herbig 1968; White 1973; Jura 1976). If the SMC interstellar lines are formed in the general IM, the trend will be toward higher ionization than is seen in our galaxy. This is primarily because there are in the SMC due to its high current rate of star formation relatively more hot stars with high far-UV luminosities capable of ionizing the IM in the SMC. Also, the electron density in a typical H I region will be lower, since the electrons come from the metals, and the gas is metal poor. Both of these effects will enhance the ionization of Ca, contrary to the observed strong Ca II lines.

If the interstellar Ca II lines in the SMC were formed in H II regions, the higher electron density would force all of the Ca into Ca II. However H II regions will be circumstellar around each OB star, yet the radial velocities of the Ca II feature and of the star are often quite different. It thus seems that the Ca II lines are truly interstellar and are formed in the general SMC interstellar medium, where hydrogen is largely neutral, as is shown by its strong 21-cm line.

Careful calculations of ionization equilibrium, including the effects of the difference in the mean far-UV radiation field and in the far-UV extinction curve, for the SMC interstellar medium would be very useful.

The relative absence of grains, which in our galaxy contain more than 90% of the Ca (Herbig 1968; Field 1974), is a much more reasonable explanation for the abnormally strong SMC interstellar Ca II lines. The gas-to-dust ratio in the SMC or more correctly, the H I gas-to-color excess ratio, (see the review by Kornneef 1983) is known to be more than ten times the galactic ratio.

b) The Radial Velocities

High-spatial-resolution 21-cm maps of the SMC have been obtained by Matthewson, Ford, and Fisher (1984) (see Matthewson and Ford 1983, Matthewson 1984). Two components of the 21-cm line, separated by about 30 km/s, are seen over the entire area of the galaxy. The radial velocities of the early-type stars in our sample are generally that of the higher-velocity component, although it is possible that as many as three of the stars have radial velocities typical of the lower-velocity gas. The velocity dispersion of the stars with respect to the gas at each point in space is 13 km/s, ignoring three stars with radial velocities relative to the gas of more than 50 km/s. The star with a v_r 60 km/s larger than that of the SMC gas was also observed by Ardeberg and Maurice (1977), whose radial velocity differs from ours by only 6 km/s. The other two kinematically peculiar stars have radial velocities of 75 ± 5 km/s.

The radial velocities of the Ca II interstellar feature, ignoring stars later than B4, are typically that of the lower 21-cm velocity. The higher velocity only is seen in two cases (AV 362 and AV 483), while both components are seen in the Ca II line in several cases. (The two components are barely resolved, and the radial velocity of the weaker of the two SMC components will not be very accurate.) Undoubtedly, more pairs of components would be seen in the interstellar Ca II line with higher-spectral-resolution optical data.

The agreement between the 21-cm and Ca II radial velocities is gratifying. It is also interesting that the column density of the lower-velocity component in the 21-cm line is significantly larger over the central regions of the SMC in the 21-cm H I maps than that of the higher-velocity line. Thus the predominance of detections of the lower velocity in the Ca II line is to be expected. Matthewson and Ford (1983) have suggested that the SMC has been torn in half by a recent near collision with the LMC. The kinematic data presented here for the interstellar Ca II lines do not conflict with this interpretation, provided that the lower-velocity gas is in front of the higher-velocity system. It is also interesting that the majority of our sample of reddened OB stars has radial velocities typical of the higher H I velocity, since less reddened OB stars may be found at either of the H I velocities. This strengthens the suggestion inferred from the interstellar Ca II lines alone that the lower-velocity gas is in front of the higher-velocity gas.

IV. SUMMARY

The interstellar Ca II line at 3933 Å has been observed in a sample of 31 reddened early-type stars in the SMC. Components arising from both galactic gas and from gas in the SMC are seen in most of the stars. The SMC components are stronger than would be seen in galactic stars with the same range of $B - V$ color excess, which is typically 0.2 mag. The abnormal strength of the Ca II lines is further compounded by the low metallicity of the SMC gas. Kinematic evidence shows that the Ca II components are interstellar, not circumstellar, and it seems unlikely that the ionization equilibrium of the H I regions can be shifted enough from Ca III (the dominant stage of ionization of Ca in our galaxy) to Ca II to explain the observed strength of the interstellar lines. Instead, we suggest that this is another manifestation of the relative paucity of grains in the SMC (already well established from studies of the gas/dust ratio). A much smaller fraction of the Ca is locked up in grains in the SMC than in a typical region in the disk of the Milky Way.

We compare the measured radial velocities of the stars and the gas with the high-sensitivity 21-cm maps of Matthewson and Ford (1983). They have interpreted these maps as implying that the SMC has split in two, presumably as a result of a near collision with the LMC. The two components of the 21-cm line are separated by about 30 km/s. Almost all the reddened stars have radial velocities corresponding to the higher-velocity gas. The interstellar Ca II lines usually have radial velocities corresponding to the lower gas velocity. Occasionally, both components are seen in Ca II, but in all such cases the stellar velocity is that of the higher-velocity gas. These observations demonstrate that the higher-velocity gas system must be behind the lower-velocity gas.

Detailed calculations of the ionization equilibrium in the SMC, including the contribution to the mean radiation field from the large population of early-type stars and the effect of the steep far-UV extinction curve, are needed. It would also be useful to observe a large sample of SMC stars at higher spectral resolution.

REFERENCES

Ardeberg, A. (1980). Astron. Astrophys. Suppl. **42**, 1.
Ardeberg, A., and Maurice, E. (1977). Astron. Astrophys. Suppl. **30**, 261.
Azzopardi, M., and Vigneau, J. (1975). Astron. Astrophys. Suppl. **22**, 285.
Boksenberg, A., and Sargent, W. L. W. (1978). Astrophys. J. **220**, 42.
Cohen, J. G. (1973). Astrophys. J. **186**, 149.
Cohen, J. G. (1975). Astrophys. J. **197**, 117.
Cohen, J. G., and Meloy, D. A. (1975). Astrophys. J. **198**, 545.
de Boer, K. S. (1983). In *Structure and Evolution of the Magellanic Clouds*, edited by S. van den Bergh and K. S. de Boer (Reidel, Boston), p. 375.
Dufour, R. J. (1983). In *Structure and Evolution of the Magellanic Clouds*, edited by S. van den Bergh and K. S. de Boer (Reidel, Boston), p. 353.
Feast, M. W., Thackeray, A. D., and Wesselink, A. J. (1960). Mon. Not. R.

Astron. Soc. **121**, 337.
Field, G. (1974). Astrophys. J. **187**, 453.
Herbig, G. (1968). Z. Astrophys. **68**, 243.
Isserstadt, J. (1978). Astron. Astrophys. Suppl. **33**, 193.
Jura, M. (1976). Astrophys. J. **206**, 691.
Kornneef, J. (1983). In *Structure and Evolution of the Magellanic Clouds*, edited by S. van den Bergh and K. S. de Boer (Reidel, Boston), p. 333.
Matthewson, D. S. (1984). Mercury **13**, 57.
Matthewson, D. S., and Ford, V. L. (1983). In *Structure and Evolution of the Magellanic Clouds*, edited by S. van den Bergh and K. S. de Boer (Reidel, Boston), p. 125.
Matthewson, D. S., Ford, V. L., and Fisher, J. L. (1984). Private communication.
McNamara, D. H., and Feltz, K. A., Jr. (1980). Publ. Astron. Soc. Pac. **92**, 587.
Nandy, K. (1983). In *Structure and Evolution of the Magellanic Clouds*, edited by S. van den Bergh and K. S. de Boer (Reidel, Boston), p. 341.
Rocca-Volmerange, B., Prévot, L., Ferlet, R., Lequeux, J., and Prévot-Burnichon, M. L. (1981), Astron. Astrophys. **99**, L5.
Sanduleak, N. (1968). Astron. J. **73**, 246.
Songaila, A. (1981). Astrophys. J. **248**, 945.
Songaila, A., and York, D. G. (1980). Astrophys. J. **242**, 976.
Spitzer, L. (1948). Astrophys. J. **108**, 276.
White, R. E. (1973). Astrophys. J. **183**, 81.